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Monitoring Soil Quality to Assess the Sustainability of Harvesting Corn Stover

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ABSTRACT

Harvesting feedstock for biofuel production must not degrade soil, water, or air resources. Our objective is to provide an overview of field research being conducted to quantify effects of harvesting corn (*Zea mays* L.) stover as a bioenergy feedstock. Coordinated field studies are being conducted near Ames, IA; St. Paul and Morris, MN; Mead, NE; University Park, PA; Florence, SC; and Brookings, SD., as part of the USDA-ARS Renewable Energy Assessment Project (REAP). A baseline soil quality assessment was made using the Soil Management Assessment Framework (SMAF). Corn grain and residue yield for two different stover harvest rates (~50% and ~90%) are being measured. Available soil data remains quite limited but sufficient for an initial SMAF analysis that confirms total organic carbon (TOC) is a soil quality indicator that needs to be closely monitored closely to quantify crop residue removal effects. Overall, grain yields averaged 9.7 and 11.7 Mg ha^{-1} (155 and 186 bu acre^{-1}) in 2008 and 2009, values that are consistent with national averages for both years. The average amount of stover collected for the 50% treatment was 2.6 and 4.2 Mg ha^{-1} for 2008 and 2009, while the 90% treatment resulted in an average removal of 5.4 and 7.4 Mg ha^{-1}, respectively. Based on a recent literature review, both stover harvest scenarios could result in a gradual decline in TOC. However, the literature value has a large standard error, so continuation of this long-term multi-location study for several years is warranted.

Corn stover, the aboveground material left in fields after corn grain harvest, was identified as a potential feedstock (Perlack et al., 2005) to help supply biofuel needed to offset a portion of the 14 million barrels of oils consumed daily by the U.S. transportation sector (NAS, 2009). It was projected to supply 256 million tons of the 1.4 billion tons of biomass (232 million Mg out of 1.3 billion Mg) estimated to be available each year. Corn stover was identified as an important feedstock because of its abundance (~35 million ha of corn were planted in 2008 and 2009) and at least the perception that it was an unused material (Nelson, 2002; Perlack et al., 2005; Biomass Research and Development Board, 2008). It was also recognized that corn yields have nearly doubled since the first energy crisis during the 1970s, that yields are expected to continue to increase in the future, and that in Iowa, farmers currently spend \$45 to \$65 ha^{-1} (\$20–\$30 acre^{-1}) to “manage” their stover (Duffy, 2010).

From an engineering perspective, harvesting stover as a major feedstock appears quite favorable, but the Billion Ton Report (BTR) projections raised many concerns among soil scientists that harvesting excessive corn stover could reduce crops yields directly (Wilhelm et al., 1986, 2004) or indirectly by diminishing TOC levels until soil’s production capacity was threatened (Johnson et al., 2006; Mann et al., 2002; Wilhelm et al., 1986; 2004).

One method for evaluating the impact of harvesting corn stover and other feedstock materials is to use a soil quality assessment. During the past 20 yr, several studies (e.g., Jokela et al., 2009; Karlen et al., 1997, 2006; Liebig et al., 2006; Wienhold et al., 2006; Zobeck et al., 2008) have used the SMAF developed by Andrews et al. (2004) to monitor and evaluate soil biological, chemical, and physical responses to various land uses, farming systems, and management practices. We expect that the potential land-use changes associated with development of a sustainable biofuel industry will present another opportunity to use the SMAF to guide and quantify long-term effects of such endeavors.

By focusing on soil quality impacts, the perception that crop residues are not important for modern grain production systems will hopefully be dispelled. Crop residues (both above and belowground) protect land from the ravages of wind and water erosion (Soil Conservation Society of America, 1979). They also supply an annual input of carbon and replenish several of the essential plant nutrients that are assimilated during crop production (Wilhelm et al., 2004). Traditionally, a limited amount of corn stover has been harvested for animal feed and bedding. This is usually done in a localized manner,

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Abbreviations: BD, bulk density; CT, conventionally-tilled; ICP–AES, inductively-coupled plasma atomic emission spectroscopy; MSC, minimum source carbon; NT, no-till; POM, particulate organic matter; REAP, Renewable Energy Assessment Project; SCI, soil conditioning index; SMAF, Soil Management Assessment Framework; TOC, total organic carbon.

Table 1. Grain yield response to crop residue removal for a varying number of years in various states.

Location	Years	Crop residue treatments	Grain yield response	Citation
IN	6	0, 1X, and 2X remaining	none	Barber, 1979
SC	3	0, 66% or 90% removed	none	Karlen et al., 1984
NE	4	0, 0.5, 1.0 to 1.5X remaining	decrease	Wilhelm et al., 1986
NE	11	0, 0.5, 1.0 or 1.5X remaining	decrease	Power et al., 1998
IA	2	removed over row	increase	Kaspar et al., 1990
WI	7	0, 1X or 2X remaining	bare decreased (5 of 7 yr) 2x decreased (6 of 7 yr)	Swan et al., 1994
MN	13	0 or1X remaining	none or decrease	Linden et al., 2000
MN	29	grain vs. silage	none	Wilts et al., 2004
Canada	30	grain vs. silage	decreased (3 of 4 yr)	Hooker et al., 2005
OH	2.5	o, 50, 75 or 100% removed	none or decreased	Blanco-Canqui and Lal, 2007

with a substantial portion of the residues being returned to the soil, often mixed with animal manure and thus not only adding carbon but also recycling other nutrients to soils in the same location (or at least on the same farm) from whence they came.

Despite the recycling that can occur when crop residues are used as animal feed and then partially recycled through the manure, long-term research has conclusively shown that crop production practices often result in TOC loss (Paustian et al., 1997). Losses are often greatest where corn is produced on soils having artificial drainage, intensive annual tillage, and less diverse plant communities. Collectively, these factors have been shown to have reduced TOC by 30 to 50% when compared to pre-cultivation levels (Schlesinger, 1985). Such TOC loss can have many detrimental effects on soil productivity (Gollany et al., 1991; Mann et al., 2002) and quality (Liebig et al., 2005; Moebius-Clune et al., 2008). However, soil and crop management practices that decrease tillage and crop residue incorporation can reduce TOC losses and may even increase TOC to a limited extent (Burke et al., 1989).

Previous long-term studies, such as those by reviewed by Paustian et al. (1997), showed the importance of preventing excessive stover harvest, which was recognized in the BTR. As a result, the BTR authors limited their estimates of available feedstock to protect soil resources from wind and water erosion (Nelson, 2002; Graham et al., 2007), but they did not account for the amount of stover required to sustain TOC levels.

Cycling of TOC is responsible, at least in part, for many qualities of productive soils (Kay, 1998; Doran et al., 1998; Doran, 2002; Janzen et al., 1998; Lal et al., 1990; Tisdall and Oades, 1982). Larson et al. (1972) showed that TOC was linearly related to the quantity of residue added, but establishing a direct linkage between stover harvest and subsequent grain yield is difficult. Some studies have shown that residue removal reduces grain and stover yield in subsequent crops (Wilhelm et al., 1986) and further lowers TOC levels (Clapp et al., 2000; Maskina et al., 1993), but others show either no effect or even increases in subsequent grain yields (Table 1). Lal (2004a) and Wilhelm et al. (2004; 2007) concluded that returning a portion of the crop residue to soils was crucial for replenishing TOC and that doing so was a fundamental requirement for the soil and crop management system to be truly sustainable.

With regard to soil quality assessment, Karlen et al. (2006) used the SMAF to evaluate long-term studies on soils in north central Iowa and southwest Wisconsin and concluded that crop rotations with at least 3 yr of forage had higher ratings than those with just corn and soybean [*Glycine max* (L.) Merr.]. For those analyses, TOC proved to be the most sensitive indicator, while soil bulk density (BD) was the least sensitive. Wienhold et al. (2006) also used the SMAF and concluded that extended crop rotations had positive impacts on soil quality indicators based on their assessment of cropping systems in the Great Plains Region. Nutrient cycling, TOC content, and productivity improved as the frequency of tillage and fallow periods were reduced and the length of crop rotations was extended. Zobeck et al. (2008) compared the SMAF and the soil conditioning index (SCI) for irrigated cropping systems near Ft. Collins, Colorado. The systems included different N fertilizer rates for no-till (NT) and conventionally-tilled (CT) corn as well as NT corn grown in rotation with barley (*Hordeum distichon* L.), soybean, and dry bean (*Phaeseolus vulgaris* L.). Both indexes detected differences between plots with very high N from those with no N. However, the SMAF seemed to make more detailed differentiation among crop management systems than the SCI. The SMAF separated the cropping systems into three groups and showed a decrease in overall soil quality as tillage intensity increased and surface residues decreased. Jokela et al. (2009) also used the SMAF as an assessment tool in Wisconsin and found that cover/companion crops incorporated into silage corn system that received manure could improve soil quality.

Our objective for this report is to present the soil quality baselines that were developed using the SMAF for several representative research locations established to examine the effects of harvesting corn stover across the eastern half of the United States. Initial grain and stover yields for the various locations are also presented to help illustrate the breadth of factors that need to be quantified to ensure feedstock harvest and biofuel production strategies are indeed sustainable.

MULTI-LOCATION APPROACH AND METHODS

In cooperation with the Idaho National Laboratory (INL) and the North Central Sun Grant Association, a Regional Partnership project plan was developed for corn stover field studies in six states. Each location has an ARS and university partner working together providing complementary knowledge, skills, and abilities so that that the maximum amount of information is being obtained at each site. A basic corn stover experiment was agreed on for each research site. It consists of no-tillage (or the least amount of tillage necessary to establish a corn crop), three rates of stover harvest (none, ~50%, and 90%), and four replications. Each location is free to add as many additional treatments to their project as needed to meet all complementary research objectives; for example, additional removal rates, tillage treatments, soil amendments, or cover crops.

Minimum Soil Measurements

A common soil sampling plan was developed to provide a baseline for assessing the long-term effects of harvesting corn stover. Replicated composite samples were to be collected to a depth of 1 m before the initial stover harvest. Preferred depth increments were 0 to 5-, 5 to 15-, 15 to 30-, 30 to 60-, and 60 to 90-cm, although there was some variation among research sites. Hand probes with an internal diameter of at least 32 mm (11/4 in) were recommended for the two near-surface increments. A mechanical probe with at least a 50 mm internal diameter was recommended for samples from 15- to 100-cm. The entire field-moist sample was to be weighed before further processing. After hand-mixing, a subsample (100 g) was removed and dried at 104°C to determine soil water content. The field-moist weight was adjusted to a dry weight and divided by the volume represented by the composite sample to provide an estimate of field bulk density.

The remaining field-moist soil sample was passed through an 8-mm screen, air-dried, and then crushed to pass a 2 mm screen. A subsample was analyzed for soil pH using either a 1:1 soil to water or soil to 0.01 M calcium chloride ($CaCl_2$) ratio as appropriate for the location (Watson and Brown, 1998; Whitney, 1998a). Another subsample was analyzed for extractable P and K concentrations using atomic absorption spectroscopy or an inductively coupled plasma–atomic emission spectrograph (ICP–AES) after extraction with Bray (Bray and Kurtz, 1945), Mehlich III (Mehlich, 1984), Olsen (Olsen et al., 1954), or 1 M ammonium-acetate (NH_4OAc) at pH 7.0 (Warncke and Brown, 1998) extracts as appropriate for the location. A third subsample was pulverized before analyzing for TOC and total nitrogen (TN) using dry combustion. Locations with calcareous soils (i.e., Morris), the amount of inorganic C was determined (Wagner et al., 1998) so that TOC could be estimated as the difference between total C and inorganic C.

At some locations, additional subsamples were retained to measure dry (Chepil, 1962) or wet (Cambardella and Elliott, 1993) aggregate stability. The former is determined by rotary sieving while wet sieving uses five sieves to separate water stable aggregates into size classes of: 4 to 8-, 2 to 4-, 1 to 2- 0.5 to 1-, and 0.25 to 0.50-mm. The data is then used to calculate percent macro-aggregation (%MA) or combined to create three water-stable, macroaggregate categories–All (0.25–8 mm), Small (0.25–2 mm), and Large (2–8 mm). Each class weight is then expressed as a fraction of the total soil mass (g kg^{-1}) with the values being used to calculate a mean weight diameter (MWD) to further characterize soil aggregation. This provides a single-number index equal to the sum of the fraction of total soil mass in each aggregate size class (including <0.25 mm), weighted by mean diameter of each size class (Vansteenbergen et al., 1991).

Additional soil analyses made at some locations included extractable Cu, Fe, Mn, and Zn using diethylene-triamine-pentaacetic acid (DTPA) as described by Whitney (1998b). Those elements were measured using ICP–AES. Microbial biomass using a fumigation-extraction procedure (Vance et al., 1987) with a K value of 0.39 for conversion of extracted C to biomass. That analysis, in conjunction with particulate organic matter (POM) as described by Cambardella and Elliott (1992), was used to quantify cycling of soil C and N within biologically active pools in the near-surface increments.

Conducting a Soil Management Assessment Framework Assessment

A SMAF assessment consists of three steps: indicator selection, indicator interpretation, and integration into a soil quality index (Andrews et al., 2004). The indicator selection step uses an expert system of decision rules to recommend indicators for inclusion in the assessment based on the user's stated management goals, location, and current practice. For the indicator interpretation step, observed indicator data are transformed into a unitless scores based on clearly defined, site-specific relationships to soil function. The soil functions of interest include crop productivity, nutrient cycling, physical stability, water and solute flow, contaminant filtering and buffering, and biodiversity. The indicator interpretation step use various factors (i.e., organic matter, texture, climate, slope, region, mineralogy, weathering class, crop, sampling time, and analytical method) to adjust threshold values in the scoring curves that are then used to assign a relative value of 0 to 1 for each type of data being collected. The integration steps allows for the individual indicator scores to be combined into a single index value. This can be done with equal or differential weighting for the various indicators depending on the relative importance of the soil functions for which they are being measured (Karlen et al., 2008).

To provide an initial soil quality baseline for these long-term studies, five soil property measurements that were available from 11 of the locations were used for an initial analysis. The SMAF released in 2004 (Andrews et al., 2004) now has scoring functions for 14 potential soil quality indicators (Wienhold et al., 2009; Stott et al., 2010), but it is not necessary to measure all of the potential indicators. A general guideline has been to use a minimum of five indicators with at least one each for soil biological, chemical, and physical properties or processes (Karlen et al., 2007). For this study, soil pH and soil-test P and K were used to represent the chemical properties, TOC was used to represent biological properties, and BD was used to represent soil physical properties.

RESULTS

The Regional Partnership was established on Ultisols, Alfisols, and Mollisols in 2008 at seven locations in six states (Table 2). Soil samples were collected to establish a baseline for several soil quality indicators. Although many analyses are still in progress, currently available data and their standard errors for each location are summarized in Table 3. Soil bulk density values were highest for the nonstructured, loamy sand Ultisols near Florence, SC (1.6–1.7 g cm^{-3}). One Mollisol site near Ames, IA, and the Alfisol site near University Park, PA, had surface bulk density values that averaged between 1.1 and 1.2 g cm^{-3}, while the remaining sites averaged between 1.3 and 1.4 g cm^{-3}. Soil organic C was lowest for the SC and nonirrigated NE sites, where values ranged from 7.4 to 9.1 and 10.7 to 14.0 g kg^{-1}, respectively. The average at all other sites and depth increments was 24.1 g C kg^{-1}. Except for the 2007 sampling of the 0 to 5 cm increment at the Mead, NE site, soil pH ranged between 6.1 and 7.6 with an overall average of 6.6. The decline in pH at the Mead site between 1998 and 2007 likely reflects soil acidification

Table 2. Corn stover regional partnership research sites, the soil series represented, and classification information.

Location	Field name	Site	Latitude	Longitude	Dominant soil or soil association
Ames, IA	70/71	1	42°1'4.8" N	–93°45'50.4" W	Clarion–Nicolet–Webster
	Bruner Farm	2	42°0'3.6" N	–93°44'9.6" W	Canisteo–Webster
	Boyd Farm	3	42°0'25.2" N	–93°47'38.40" W	Clarion–Nicolet–Webster
Brookings, SD	Brookings	4	44°12'7.2" N	–96°28'22.8" W	Kranzburg–Brookings
Florence, SC	PDREC	5	34°10'12" N	–79°26'34.8" W	Goldsboro–Lynchburg–Coxville
Morris, MN	Chisel plow	6a	45°40'58.8" N	–95°48'7.2" W	Barnes–Aastad
	No-till 1995	6b			
	No-till 2005	6c			
Mead, NE	Irrigated	7	41°9'36" N	–96°24'36" W	Tomek
	Rainfed	8	41°8'60" N	–96°24' W	Aksarben
St. Paul, MN	Rosemount	9	44°42'57.6" N	–93°5'60" W	Waukegan
	Lamberton	10	44°14'13.2" N	95°18'28.8" W	Normania–Ves–Webster
	Faribault	11	44°21'36" N	–93°12'10.8" W	Garwin
University Park, PA	University Park	12	40°51'36" N	–77°50'60" W	Opequon–Hagerstown complex

Site	Series	Classification
1, 3	Clarion	fine-loamy, mixed, superactive, mesic Typic Hapludoll
1, 3	Nicollet	fine-loamy, mixed, superactive, mesic Aquic Hapludoll
2	Canisteo	fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll
1, 2, 3 & 10	Webster	fine-loamy, mixed, superactive, mesic Typic Endoaquoll
4	Kranzburg	fine-silty, mixed, superactive, frigid Calcic Hapludoll
4	Brookings	fine-silty, mixed, superactive, frigid Pachic Hapludoll
5	Goldsboro	fine-loamy, siliceous, subactive, thermic Aquic Paleudult
5	Lynchburg	fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults
5	Coxville	fine, kaolinitic, thermic Typic Paleaquults
6	Barnes	fine-loamy, mixed, superactive, frigid Calcic Hapludoll
6	Aastad	fine-loamy, mixed, superactive, frigid Pachic Argiudoll
7	Tomek	fine, smectitic, mesic Pachic Argiudoll
8	Aksarben	fine, smectitic, mesic Typic Argiudoll
9	Waukegan	fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll
10	Normania	fine-loamy, mixed, superactive, mesic Aquic Hapludoll
10	Ves	fine-loamy, mixed, superactive, mesic Calcic Hapludoll
11	Garwin	fine-silty, mixed, superactive, mesic Typic Endoaquoll
12	Opequon	clayey, mixed, active, mesic Lithic Hapludalf
12	Hagerstown	fine, mixed, semiactive, mesic Typic Hapludalf

associated with the multiple years of N application for corn production. Soil-test P was very high at the PA site, presumably because of prior animal manure applications on this long term, no-till site. Values at the SC site were also high for crop production but less than half the level reported for PA. Soil-test P values were adequate for crop production at all other sites. Soil-test K was high for the irrigated NE site, but within expected ranges and adequate for crop production at the other locations.

A SMAF analysis was performed for each depth increment at the various sites (Table 4). Based on the five indicators, all sites except Mead, NE, had a surface soil index score of 0.8 or greater. This means the surface zone for the soils being used for these studies were functioning at approximately 80% of their inherent value when the samples were collected. The Mead site had surface index values of 0.77 and 0.73 for the two sampling dates (1998 and 2007) that were available from that site. The second and third depth increments (5 to 10- and 10 to 30-cm) were even lower with values ranging between 0.53 and 0.69 (Table 4). The SMAF analysis for individual indicators shows that total organic carbon, soil-test P, and bulk density had the lowest values, especially for the Aksarben silt loam soil (fine, smectitic, mesic Typic Argiudolls). Presumably, the low TOC at the Mead site also contributed to the low BD score (which indicates a higher than desired BD for optimum crop production).

Corn grain and stover yields were measured at each of the research sites (Table 5). Grain yields in 2008 were very low at Florence, SC, due to a severe drought during anthesis. The highest nonirrigated corn grain yields were measured in an on-farm trial in Rice County, MN. Overall, grain yields averaged 9.7 and 11.7 Mg ha^{-1} (155 and 186 bu $acre^{-1}$) in 2008 and 2009. These values are consistent with the national corn grain yields for both years (USDA-NASS, 2009) and confirm that our sites are representative of U.S. corn production. The very high irrigated yields at the Mead site in 2009 were the result of excellent weather conditions such that the crop did not suffer water or heat stress during the growing season and achieved physiological maturity before killing frost.

The average amount of stover removed for all studies at each location is shown in Table 5 for the 2008 and 2009 growing seasons. With the exception of the Mead non-irrigated site, where there is no 50% treatment, and the Rice County (St. Paul, MN) site, where severe lodging in 2008 required operating the combine head at a very low level for both stover removal treatments, the average amount of stover collected for the high-cut treatment was 2.6 and 4.2 Mg ha^{-1} for 2008 and 2009,

Table 3. Baseline soil quality indicator values at sites established to quantify effects of harvesting corn stover as a bioenergy feedstock.

Site†	State	Depth	Year sampled	BD	SE	TOC‡	SE	pH	SE	P	SE	K	SE
		cm		g cm^{-3}		g kg^{-1}				g kg^{-1}		g kg^{-1}	
1	IA	0–5	2005	1.06	0.04	26.2	1.1	6.4	0.03	32	1	133	3
1	IA	5–15	2005	1.14	0.01	22.8	0.4	6.4	0.06	24	1	93	2
2	IA	0–15	2007	1.25	0.01	53.8	0.03	7.7	0.1	31	2	129	11
3	IA	0–15	2007	1.37	0.01	19.1	0.02	6.7	0.03	22	2	95	7
4	SD	0–5	2008	1.35	0.10	27.8	0.2	6.7	0.2	23	0.3	187	6
4	SD	5–15	2008	1.47	0.03	23.8	0.2	7.0	0.2	19	0.3	156	5
5	SC	0–5	2008	1.58	0.03	9.1	0.04	6.6	0.1	72	5	111	4
5	SC	5–10	2008	1.73	0.03	8.1	0.04	6.4	0.1	42	3	79	3
5	SC	10–15	2008	1.75	0.03	7.4	0.04	6.1	0.1	26	2	67	2
6a	MN	0–5	2005	1.26	0.14	24.8	1.6	6.8	0.2	21	3	178	8
6a	MN	5–15	2005	1.29	0.14	22.3	1.5	6.8	0.2	17	3	153	4
6b	MN	0–5	2005	1.37	0.15	27.5	1.5	6.1	0.2	35	4	178	6
6b	MN	5–15	2005	1.41	0.09	20.4	1.3	6.3	0.2	17	2	132	5
6c	MN	0–5	2005	1.24	0.10	25.4	0.6	6.0	0.2	26	2	250	15
6c	MN	5–15	2005	1.38	0.08	22.0	0.7	6.0	0.2	23	2	155	6
7	NE	0–7.5	2008	1.32	.05	21.0	0.4	7.6	0.1	24	3	544	21
7	NE	7.5–15	2008	1.21	.03	17.4	0.2	7.6	0.1	12	2	336	24
7	NE	15–30	2008	1.29	.01	17.3	0.2	7.4	0.1	13	1	248	15
8	NE	0–5	1998	1.20	0.01	14.0	0.2	6.6	0.1	22	10	290	–§
8	NE	5–10	1998	1.34	0.06	12.7	0.2	6.5	0.1	11	4	206	–
8	NE	10–30	1998	1.36	0.02	10.7	0.2	6.6	0.1	5	3	153	–
8	NE	0–5	2007	1.33	0.01	17.4	0.2	5.3	0.2	24	6	283	–
8	NE	5–10	2007	1.45	0.02	13.2	0.2	6.0	0.1	7	2	217	–
8	NE	10–30	2007	1.44	0.01	11.5	0.2	6.6	0.1	4	2	166	–
10	MN	0–5	2008	–	–	–	–	6.5	0.5	19	13	224	59
10	MN	5–15	2008	–	–	–	–	6.4	0.7	6	1.9	178	28
11	MN	0–5	2008	0.82	0.19	44.5	0.2	–	–	–	–	–	–
11	MN	5–15	2008	1.19	0.25	40.3	0.1	–	–	–	–	–	–
12	PA	0–5	2008	1.10	0.02	26.0	0.06	6.9	0.02	172	7	276	9
12	PA	5–15	2008	1.19	0.01	13.4	0.03	6.3	0.06	96	5	186	8

† See Table 2 for detailed information regarding each experimental site.
‡ Total organic carbon (TOC) is determined by subtracting inorganic C from total combustible C.
§ Data not available

respectively. The 90% treatment resulted in an average removal of 5.4 and 7.4 Mg ha^{-1}, respectively.

DISCUSSION

We recognize that the amount of data available for this initial SMAF analysis is very limited, so our interpretations are very guarded, but overall, it appears that TOC is the factor that needs to be improved the most. At the Florence site, soil-test K in the 5 to 10 and 10 to 15 cm increments had scores of 0.57 and 0.51 indicating it too should be increased, but because of the low amount of kaolinitic clay in this soil, this change may not be very feasible until TOC and the associated cation exchange capacity is increased (Karlen et al., 1984; Hunt et al., 1996). The BD score for the 5 to 10 and 10 to 15 cm increments at Florence was also quite low, but this was not unexpected considering soils in this area have very well-defined Eluvial (E) horizons that generally require in-row tillage to physically disrupt them on an annual basis (Busscher et al., 1986). Based on these preliminary analyses, we anxiously await additional data to determine if and how these indicators change in response to the stover harvest treatments.

Based on crop residue studies during the first energy crisis (e.g., Larson, 1979), reviews written since the resurgence of interest in sustainable feedstock production (e.g., Johnson et al., 2009; Wilhelm et al., 2004, 2007) and the soil quality assessment data showing that TOC had relatively low scores, the importance of annual carbon input with regard to maintaining TOC and thus soil quality is quite evident.

Crop residues provide multiple ecosystem services. Through photosynthesis, plants provide the building blocks or raw material for SOM. Plant residue and rhizodeposition contribute both directly and indirectly to formation of aggregates (Tisdall, 1996; Tisdall and Oades, 1982) and indirectly assist or aid formation of stable TOC. Crop residue amount and placement have significant and complex effects on soil water and thermal regimes, which in turn have important consequences for soil C dynamics (Power and Doran, 1988). Sauer et al. (1998) showed that crop residue on the soil surface strongly influences soil microclimate. The value of crop residue to avoid and/or minimize wind and water erosion, and improving soil hydrology has been well documented (e.g., Gilley et al., 1986; Gregorich et al., 1998; Larson, 1979; Lindstrom, 1986; Lindstrom and Holt, 1983; Mohamoud and Ewing, 1990; Savabi and Stott, 1994; Lyles and Allison, 1981; Sauer et al., 1996; Soil Conservation Society of America, 1979). Erosion decreases productivity by removing the organic rich topsoil (Gollany et al., 1992). Any removal of crop residue must be limited by the need to retain sufficient soil cover to keep

Table 4. Initial soil quality indicator scores and an overall index value (SQI) for several Regional Partnership corn stover research sites.

Site†	Depth, cm	TOC‡	pH	P	K	BD	SQI
1	0–5	0.71	1.00	1.00	0.77	0.99	0.89
1	5–15	0.57	1.00	1.00	0.63	0.99	0.84
2	0–15	1.00	0.94	1.00	0.76	0.99	0.94
3	0–15	0.40	1.00	0.99	0.64	0.88	0.78
4	0–5	0.77	1.00	1.00	0.89	0.92	0.91
4	5–15	0.61	0.99	0.98	0.83	0.65	0.81
5	0–5	0.92	1.00	1.00	0.70	0.65	0.85
5	5–10	0.63	1.00	1.00	0.57	0.29	0.70
5	10–15	0.78	1.00	1.00	0.51	0.36	0.73
6a	0–5	0.60	0.99	0.98	0.87	0.99	0.89
6a	5–15	0.49	0.99	0.97	0.82	0.98	0.85
6b	0–5	0.71	1.00	1.00	0.87	0.88	0.89
6b	5–15	0.41	1.00	0.97	0.77	0.80	0.79
6c	0–5	0.63	1.00	1.00	0.96	0.99	0.92
6c	5–15	0.49	1.00	1.00	0.82	0.86	0.83
7	0–7.5	0.37	0.95	1.00	1.07	0.80	0.84
7	7.5–15	0.25	0.95	0.92	1.06	0.98	0.83
7	15–30	0.25	0.96	0.94	1.04	0.86	0.81
8	0–5	0.15	1.00	0.99	1.05	0.66	0.77
8	5–10	0.12	1.00	0.90	1.01	0.40	0.69
8	10–30	0.09	1.00	0.44	0.94	0.38	0.57
8	0–5	0.23	0.97	1.00	1.05	0.41	0.73
8	5–10	0.13	1.00	0.69	1.02	0.30	0.63
8	10–30	0.11	1.00	0.29	0.96	0.30	0.53
12	0–5	0.85	0.99	0.85	1.05	0.97	0.94
12	5–15	0.27	1.00	1.00	0.99	0.83	0.82

† See Table 2 for specific location and site information.

‡ TOC, total organic carbon, BD, bulk density; SQI, soil quality indicator.

soil loss by erosion within tolerable limits (T values) established by NRCS (Larson, 1979; Nelson, 2002). The BTR addressed soil erosion protection quite well, but T values currently used for erosion tolerance do not necessarily provide an adequate level of protection to prevent environmental degradation and yield loss (Mann et al., 2002). Lal (2004b) questioned the ability of crop residues to make a significant contribution to energy needs without negative consequences on soil quality due to increased erosion and loss of TOC. Documenting the intrinsic value of crop residue remains a primary objective for both the ARS-REAP and Regional Partnership teams.

To develop sustainable feedstock production strategies, accurate estimates of the amount of C inputs required to maintain TOC and control soil erosion are needed. Johnson et al. (2006) used empirical data and linear regression to correlate C inputs to TOC and proposed minimum source carbon (MSC) as a term to describe the annual C input needed to ensure no net change in TOC content. Since the review (Johnson et al., 2006), several other studies allowing MSC estimates have resulted in similar aboveground MSC estimates (Johnson et al., 2009). Using above-ground non-grain C inputs, MSC was 2.5 ± 1.7 Mg C ha^{-1} yr^{-1} ($n = 28$) for different crops and tillage practices at several experimental sites. This was slightly higher than the mean MSC of 2.2 ± 1.1 Mg C ha^{-1} yr^{-1} ($n = 21$) presented by Johnson et al. (2006). These studies also suggest that moldboard plow systems had higher MSC requirements than those with no tillage. Similar results were also reported by Bayer et al. (2006). Furthermore, assuming a C concentration of 400 g kg^{-1} (40%) in corn stover, 6.25 Mg ha^{-1} yr^{-1} must be left in the field to supply 2.5 Mg C ha^{-1} yr^{-1} of source C. This agrees with the value of 6 Mg ha^{-1} of corn stover reported by Larson et al. (1972) as the amount required for sustaining TOC levels.

The long-term goal for this multi-location study is to quantify the impact of these stover removal rates on TOC, but that will take time. Therefore to project the potential effects on TOC, Table 6 was created to provide an estimate of available feedstock at various grain yield levels and for two harvest indices (0.50 and 0.55). The latter value was included because many current projections have assumed a 1:1 dry corn grain to dry stover ratio, but with recent advances in plant breeding this is not necessarily true for modern corn hybrids (Johnson et al., 2009). The importance of achieving high grain yields before removing stover is also illustrated by the values in Table 6. This is consistent with the graph used by Wilhelm et al. (2007) to illustrate the impact of yield on the amount of stover available for uses other than maintaining TOC.

Using Tables 5 and 6, various scenarios can be constructed to project long-term effects of the treatments on TOC and thus soil quality. For example, using the average 2008 grain yield of 9.7 Mg ha^{-1}, the projected amount of available stover feedstock at harvest indices of 0.50 or 0.55 would be 1.9 or 0.5 Mg ha^{-1}. Both values are less than the average (2.6 Mg ha^{-1}) amount that was harvested. Average grain yields were higher in 2009 (11.7 Mg ha^{-1}) but so was the average stover removal rate (4.2 Mg ha^{-1}), which again exceeded the "available" estimates for both harvest indices. Obviously, if the 50% scenario is not favorable, the 90% scenario will have even more negative potential consequences. Based on these scenarios, a gradual decrease in TOC could easily be anticipated, but there is a large standard error associated with the maintenance level used for projections in Table 6 (Johnson et al., 2009), so there really is no substitute for a series of long-term studies under a variety of management and climatic conditions to accurately assess the effects of harvesting crop residues as a biofuel feedstock.

SUMMARY AND CONCLUSIONS

An effective and successful multi-location, multi-region bioenergy feedstock production study has been established. Soil, crop yield, and stover removal data have been collected for 2 yr to help quantify long-term effects of low and high stover harvest strategies. Based on an initial, but very limited SMAF analysis, it appears that TOC is the soil quality indicator that needs to be monitored most closely to quantify crop residue removal effects. This is being addressed not only by measuring harvested and residual amounts of crop residue, but also by incorporating cover crops and using higher plant populations in twin-row planting systems to increase TOC input. Overall, grain yields averaged 9.7 and 11.7 Mg ha^{-1} (155 and 186 bu $acre^{-1}$) in 2008 and 2009, values that are consistent with national projections and confirmation that the distribution of our research sites is representative of corn production throughout the United States. The average amount of stover collected for the 50% treatment was 2.6 and 4.2 Mg ha^{-1} for 2008 and 2009, respectively, while the 90% treatment resulted in an average removal of 5.4 and 7.4 Mg ha^{-1}, respectively. Based on current literature data, removal rates for both scenarios could

Table 5. Range of corn grain yields and average stover removal quantities for the 2008 and 2009 growing seasons at 12 Regional Partnership research sites.

Location†	Range in grain yield (Mg ha^{-1}) at 155 g kg^{-1} water content		2008 Stover harvest (Mg ha^{-1}) at 0 g kg^{-1} water content		2009 Stover harvest (Mg ha^{-1}) at 0 g kg^{-1} water content	
	2008	2009	50%	90%	50%	90%
Ames, IA	9.9–12.9	8.3–12.4	3.9	6.4	3.4	8.0
Florence, SC	3.9–4.9	8.4–9.4	2.5	4.7	4.1	8.3
Brookings, SD	7.0–7.1	9.6–9.7	3.2	7.0	6.1	7.5
Morris, MN	7.1–11.7	6.5–10.0	1.3	2.8	4.9	6.2
St. Paul, MN	9.2–14.8	11.0–14.7	8.3	8.5	3.9	8.3
Mead, NE (I)‡	7.2–11.7	14.3–20.7	1.7	3.4	3.6	7.0
Mead, NE (NI)	4.7–7.6	4.7–7.7	—‡	3.9	–	4.5
University Park, PA	7.8–8.3	12.0–13.0	3.1	6.3	3.4	9.2

† See Table 2 for detailed information regarding each experimental site.

‡ The nonirrigated study has only two residue removal treatments–yes or no

Table 6. Calculated available corn stover feedstock at two harvest indices after returning the average† amount of 6.25 Mg ha^{-1} projected by Johnson et al. (2009) to sustain TOC.

Grain yield		Harvest index‡	Available feedstock		Harvest index†	Available feedstock	
bu acre^{-1}	Mg ha^{-1}		t acre^{-1}	Mg ha^{-1}		t acre^{-1}	Mg ha^{-1}
150	9.4	0.50	0.76	1.70	0.55	0.1	0.3
170	10.7	0.50	1.23	2.76	0.55	0.5	1.1
190	11.9	0.50	1.71	3.82	0.55	0.9	2.0
210	13.2	0.50	2.18	4.88	0.55	1.3	2.9
230	14.4	0.50	2.65	5.94	0.55	1.7	3.7
250	15.7	0.50	3.12	7.00	0.55	2.1	4.6
270	16.9	0.50	3.60	8.06	0.55	2.4	5.5
290	18.2	0.50	4.07	9.12	0.55	2.8	6.4

† Please note that this average value is based on 28 published studies examining crop residue.

‡ Defined as dry grain weight/(dry grain weight + dry aboveground biomass weight) at physiologic maturity.

result in a gradual decline in TOC, but there is a large standard error associated with those estimates, emphasizing the need for continuing this and other long-term studies for several years.

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